

Ian W. Eames, London South Bank University

Optimising a total food refrigeration system



Introduction

- Outline the aim of this part of the project.
- Describe a new interactive refrigerator simulator and its uses.
- Describe a new interactive refrigeration system simulator based around a cold-store or freezer installation and its uses.



Project aims

The general objective of this part of the project is to develop scientifically based models of refrigeration systems common across the food chain, so as to allow study of performance and component choice.



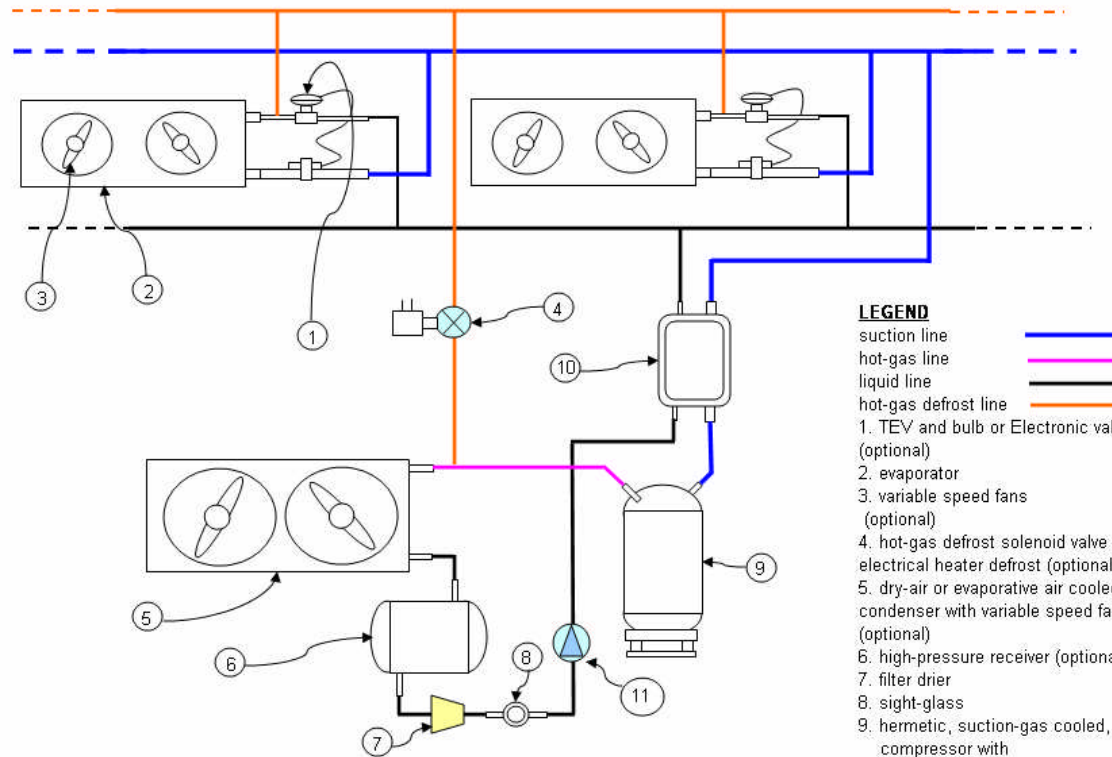
What type of system?

Our preliminary investigations suggested that Air-Air DX types of refrigerators are most commonly used by the food processing industry – therefore this is where we started modelling ...



Our preliminary model

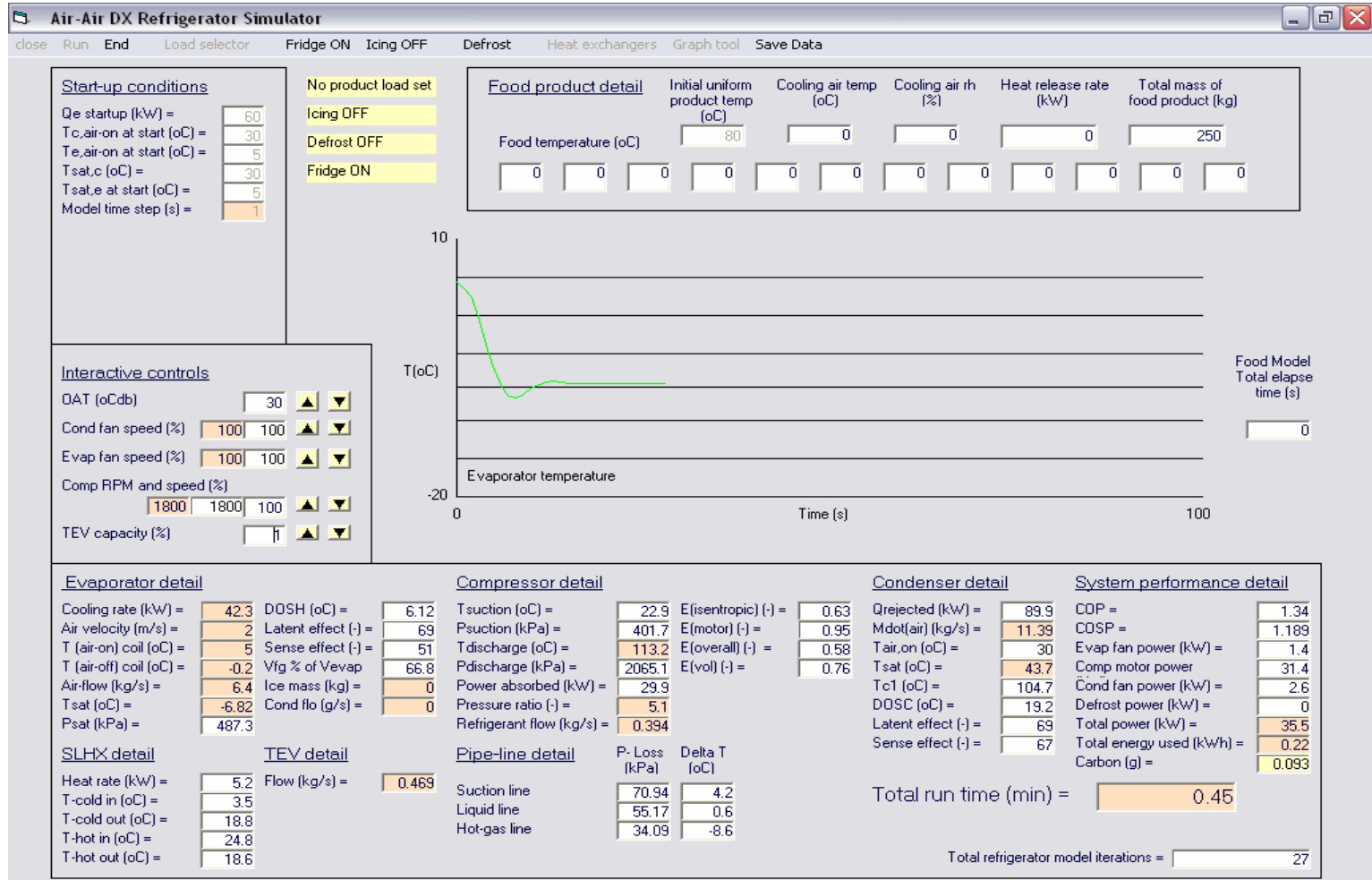
Air-Air D-X System Model



LEGEND

- suction line —
 - hot-gas line —
 - liquid line —
 - hot-gas defrost line —
1. TEV and bulb or Electronic valve (optional)
 2. evaporator
 3. variable speed fans (optional)
 4. hot-gas defrost solenoid valve (optional) or electrical heater defrost (optional)
 5. dry-air or evaporative air cooled condenser with variable speed fans (optional)
 6. high-pressure receiver (optional)
 7. filter drier
 8. sight-glass
 9. hermetic, suction-gas cooled, compressor with variable speed motor (optional)
 10. suction-line heat exchanger (optional)
 11. Refrigerant pump (optional)

An interactive refrigerator development model



What the software provides:

Before pressing the RUN button you can ...

- Input the required design cooling duty of the evaporator.
- Select the cooling efficiency of the condenser and/or evaporator.
- Select the start-up evaporator and condenser air-on conditions.
- Select the start-up conditions for compressor, condenser and evaporator fan speeds.
- Select TEV capacity.
- Select the time-step of the data collection – normally up to 100hrs of simulated running time – but more or less if required.
- Select the scale of the Time axis in the graphical display.

DEFAULT VALUES USED FOR ALL THE ABOVE IF NO SELECTION MADE



When the model is running ...

It allows you to:

- Vary evaporator and condenser fan speeds.
- Vary compressor speed.
- Vary TEV capacity
- Vary Outdoor temperature

When the model is running:

On-screen System performance data are displayed continuously, including total power, kWh consumed and CO₂ emissions.

Graphical output is provided.

The model will continue running until you tell it to stop by pressing END!



When the RUN-TIME is completed ...

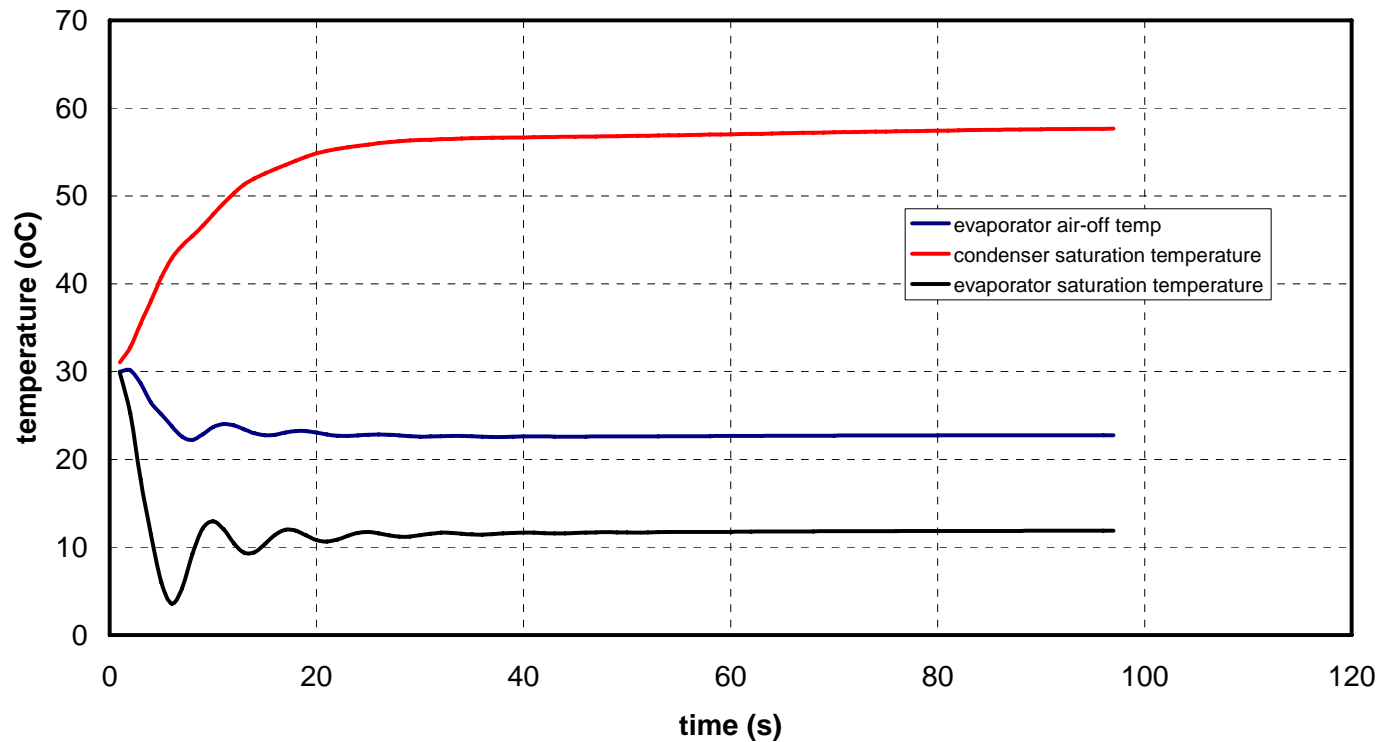
You can :

- SAVE your data to file for later spreadsheet analysis.
- Select different operating conditions and RUN the model again.

Some output data...

- High temperature start-up

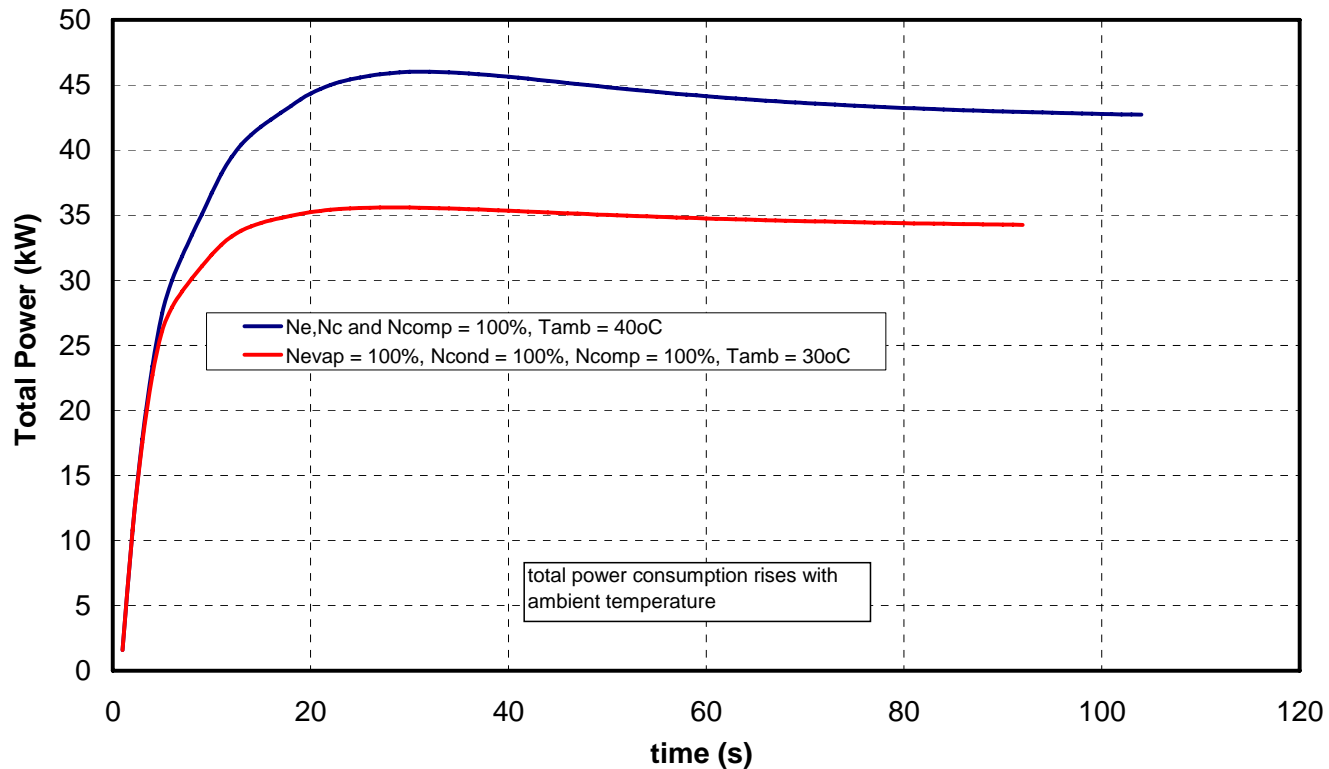
Variation in system temperatures during high temperature start-up with no product load



More results ...

Ambient temperature and power

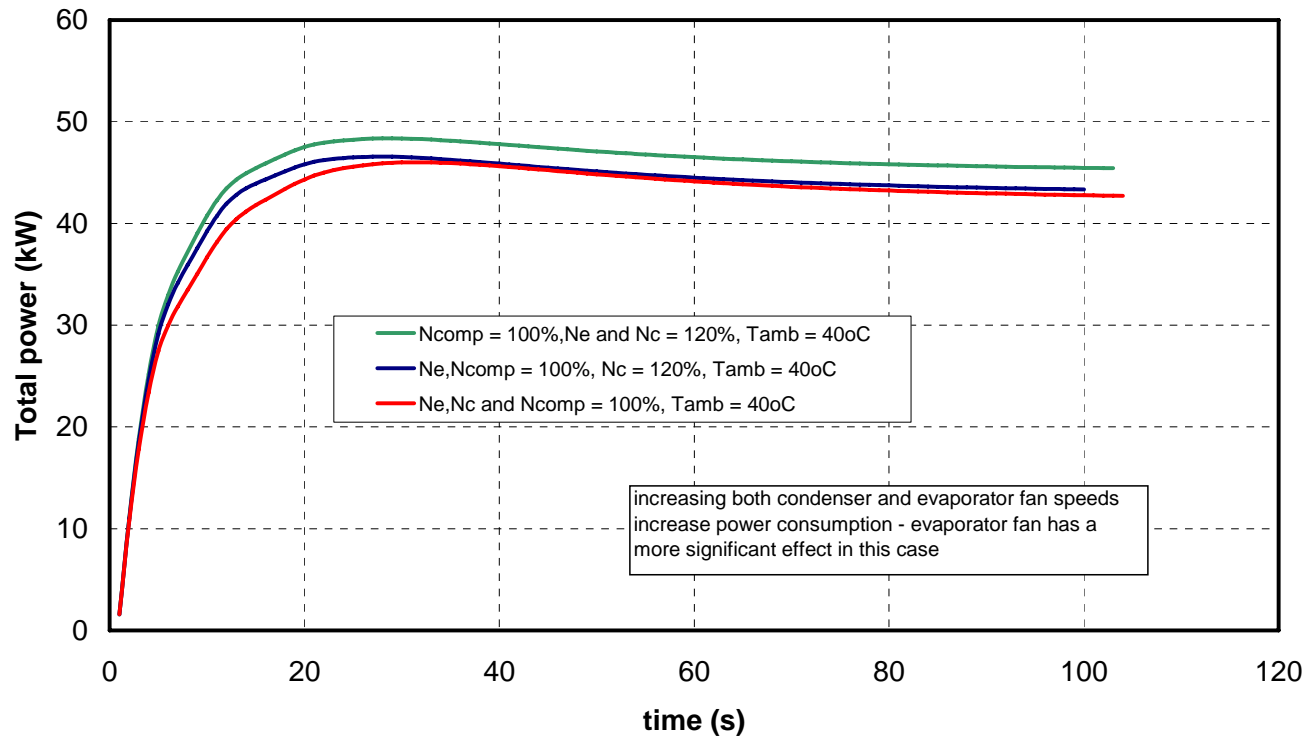
Variation in total power consumption with ambient temperature



More results ...

Fan speed effects at high ambient temperature

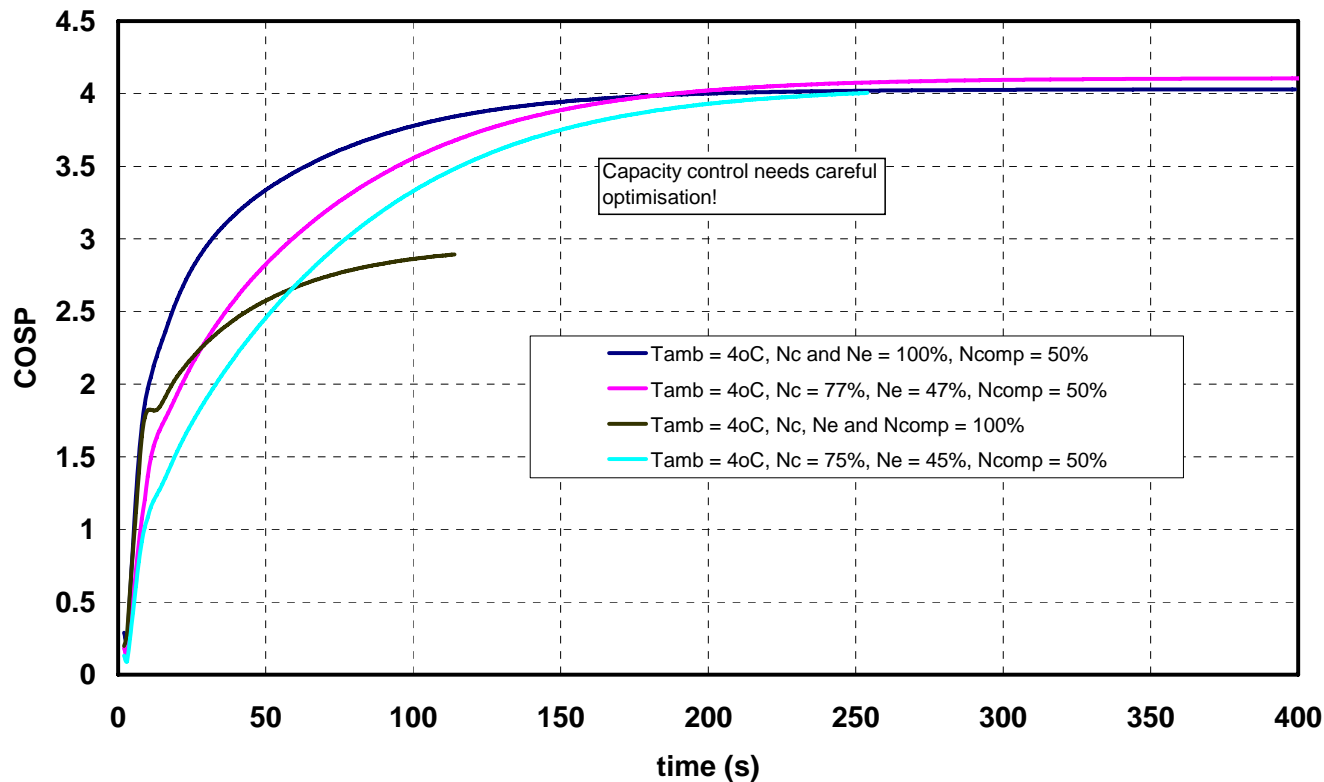
Effect of fan speeds on total power consumption at high ambient temperatures



More results....

Capacity control at low ambient temperatures

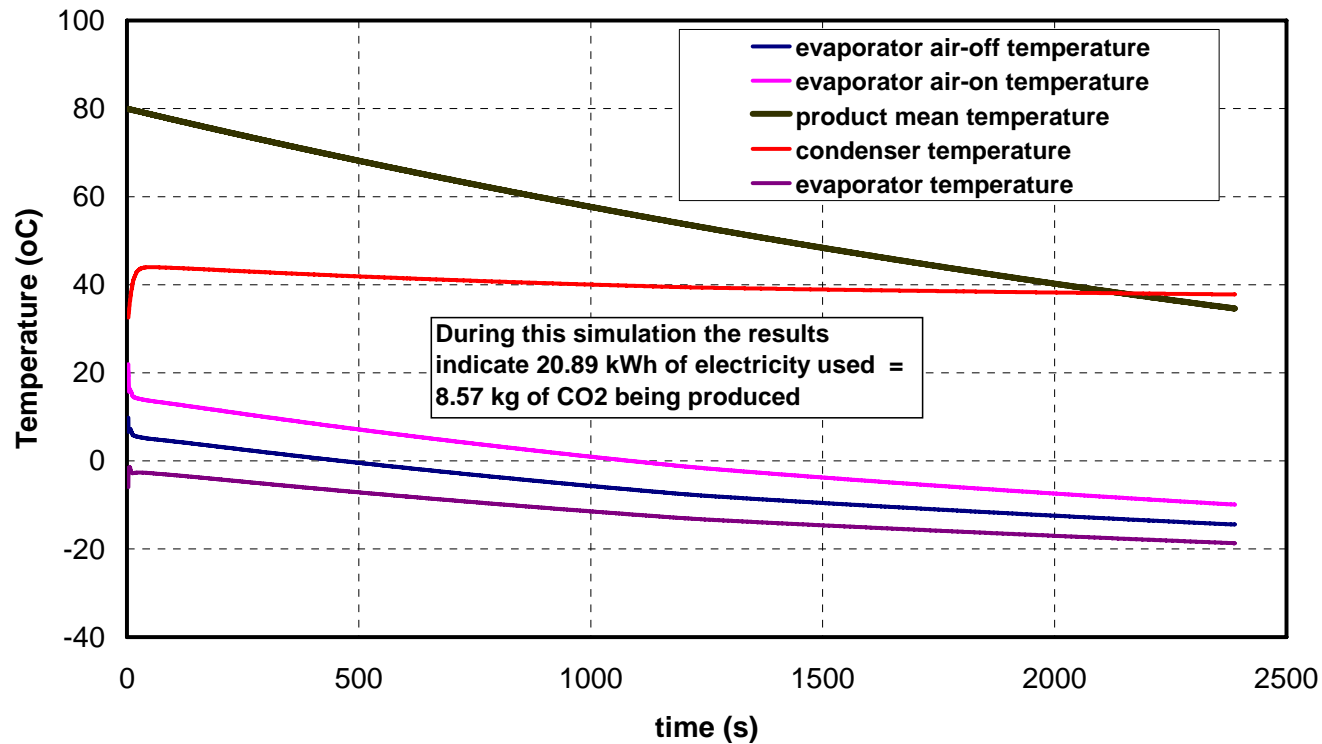
Capacity control at low ambient temperatures



More results

Food product cooling

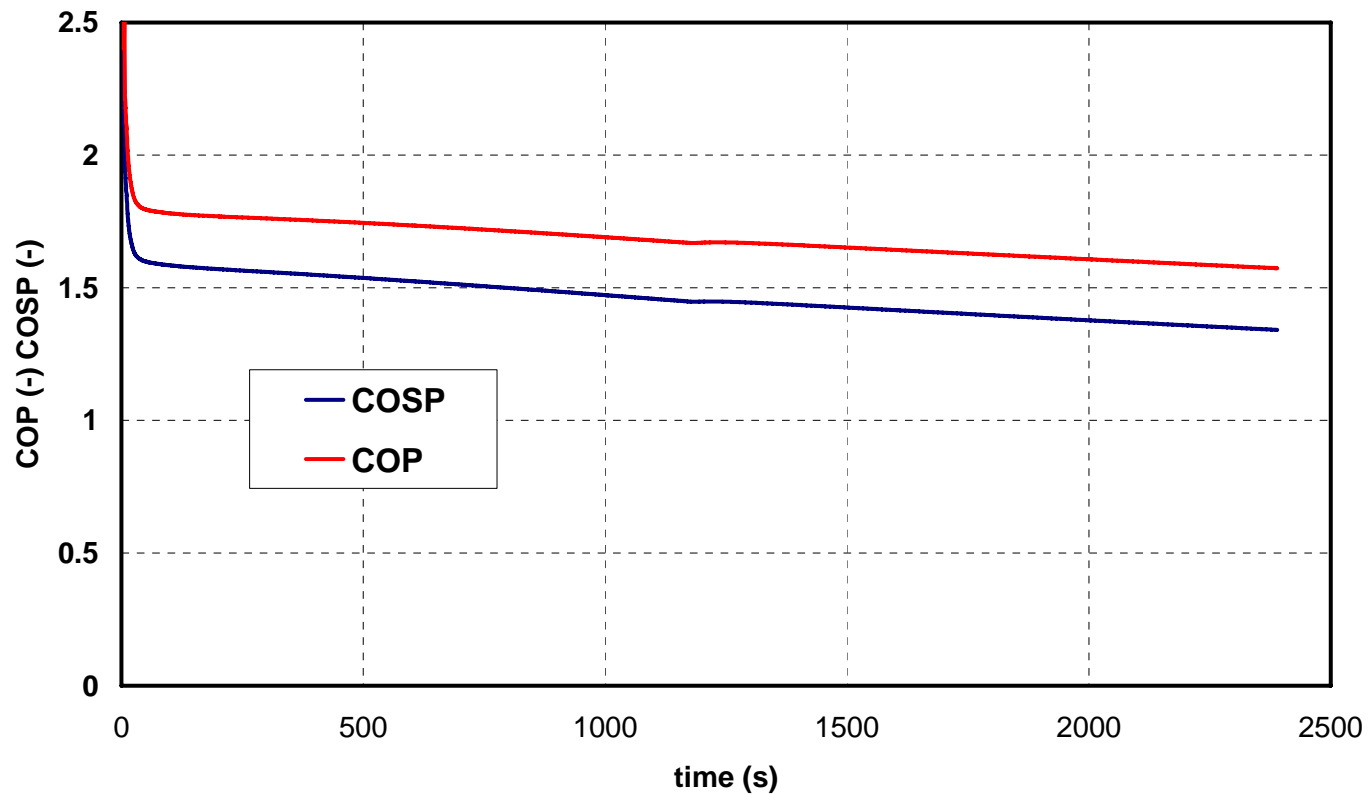
Variation in system temperatures
with time during 250 kg of pie product being cooled



More results ...

Variation in efficiency during product cooling

Variation in COP and COSP with time during product cooling process

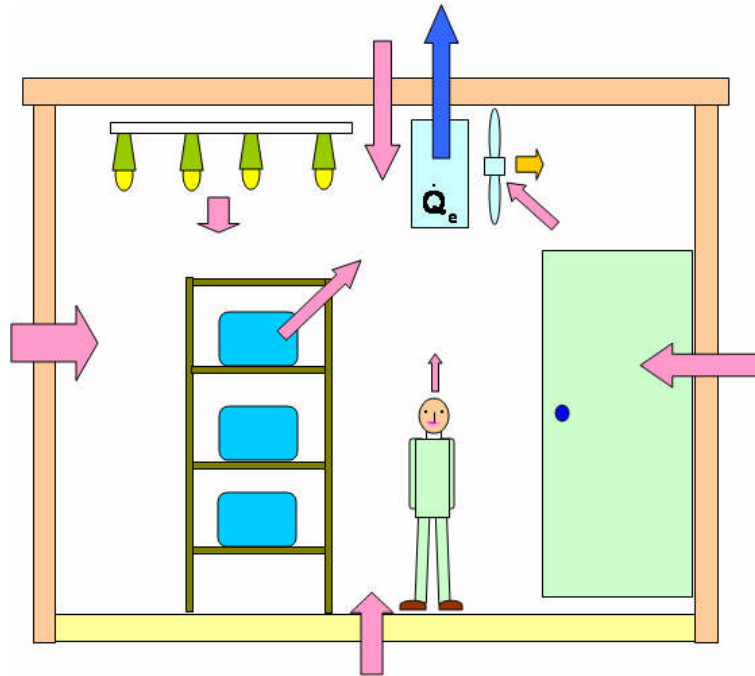


Cold-store simulator

- An interactive software that allows you to model the energy performance of cold or freezer room systems, including the refrigerator over a period of time.
- This software allows you to simulate product loading and unloading schedules with varying ambient conditions if needed.



What the store model allows for:



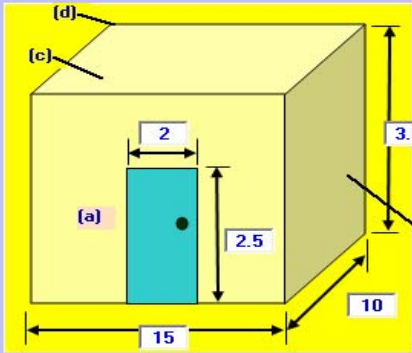
Heat gains include:

- Product
- Fabric
- Racking
- Lighting
- People
- Infiltration
- Evaporator
- Fans

Cold store Set-up Screen



Dynamic Cold Store Model Set-up
Close Set ReDo Help



Temperature Data

	max	min	
Wall (a) DAT (oC)	20	15	variable
Wall (b) DAT (oC)	20	15	variable
Wall (c) DAT (oC)	20	15	variable
Wall (d) DAT (oC)	20	15	variable
Ceiling DAT (oC)	20	15	variable
Ground temperature (oC)	10		

Design-point store temperature (oCdb) = Store pull-down time (mins) =

Construction detail (Help Note 1)

Floor thickness (mm) (Note 2) =

Inner wall type (Note 3) =

Ceiling T type (Note 3) =

Racking type (Note 4) =

Racking storage area (m2) =

Ceiling U-value (W/m2K) =

Walls U-value (W/m2K) =

Floor U-value (W/m2K) =

Continuous cooling loads

Air infiltration due to normal internal over-pressure (Pa) (Note 5) =

Number of people working in store (Note 6) =

Continuous lighting load (W) =

Continuous ancillary fan motor load (W) =

Under floor heating load (W) =

Ancillary fan load (W) =

Intermittent heat gains during product loading/unloading

Additional lighting load (W) =

Additional ancillary equipment load (W) =

Average number of additional people (Note 6) =

Door Flow Factor (Note 7) =

Door Effectiveness (Note 7) =

Results

Continuous Heat Gains in kW at design conditions:

Infiltration =

Internal (ex-product) =

Structural =

Total (kW) =

Intermittent Heat Gains in kW:

Internal (ex-product) =

Door-opening gain (Note 7) =

Total (kW) =

Store Heat Capacity (kJ/K) =

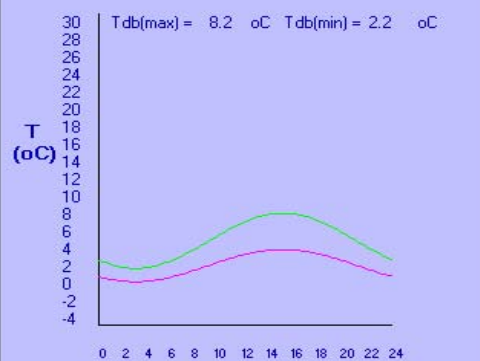
Refrigerator design cooling duty (kW) =

Refrigerator max cooling duty (kW) =

Set ReDo Fixed Help
Location Month Plot Graph

February
Show Data

Tdb(max) = 8.2 oC Tdb(min) = 2.2 oC



London in February

OAT maximum deviation = oC

OAT minimum deviation = oC

Loading Schedule Product list Help

Model run-time

Start day hour min

End day hour min

Cold-space model start-up data

Cold space temperature (oC) =

Cold space %rh =

Default Time step = 10s

Product Loading Schedule

Schedule Number =

Product =

Product Units =

Product code =

Loading temperature (oC) =

Air velocity across product (m/s) =

Load Start Time = day hour min

Product units loaded =

Product units unloaded =

Loading time (mins) =

Door open time during loading (mins) =

Target cooling time (mins) =

start
Sample Output ...
VCRmodel 7Jan08
IWEames Prese...
Partnerpowerp...
VCRmodel - Mic...
VCR v1.0: Singl...
EN
07:48

Close-up of store set-up screen...



Close Set ReDo Help

Construction detail (Help Note 1)

Floor thickness (mm) (Note 2) =

Inner wall type (Note 3) =

Ceiling Type (Note 3) =

Racking type (Note 4) =

Racking storage area (m2) =

Ceiling U-value (W/m2K) =

Walls U-value (W/m2K) =

Floor U-value (W/m2K) =

Continuous cooling loads

Air infiltration due to normal internal over-pressure (Pa) (Note 5) =

Number of people working in store (Note 6) =

Continuous lighting load (W) =

Continuous ancillary fan motor load (W) =

Under floor heating load (W) =

Ancillary fan load (W) =

Intermittent heat gains during product loading/unloading

Additional lighting load (W) =

Additional ancillary equipment load (W) =

Average number of additional people (Note6) =

Door Flow Factor (Note7) =

Door Effectiveness (Note7) =

Results

Continuous Heat Gains in kW at design conditions:

Infiltration

Internal (ex-product)

Structural

Total (kW) =

Intermittent Heat Gains in kW:

Internal (ex-product) =

Door-opening gain (Note7) =

Total (kW) =

Store Heat Capacity (kJ/K)

Refrigerator design cooling duty (kW) =

Refrigerator max cooling duty (kW) =

Temperature Data

	max	min
Wall (a) DAT (oC)		<input type="text" value="no selection"/>
Wall (b) DAT (oC)		<input type="text" value="no selection"/>
Wall (c) DAT (oC)		<input type="text" value="no selection"/>
Wall (d) DAT (oC)		<input type="text" value="no selection"/>
Ceiling DAT(oC)		<input type="text" value="no selection"/>
Ground temperature (oC)	<input type="text" value="10"/>	
Design-point store temperature (oCdb) =	<input type="text" value="5"/>	Store pull-down time (mins) = <input type="text" value="180"/>

Refrigerator design screen

VCR v1.0: Single-Stage Design Point Data Input Screen

Exit File Project Run Tools Help

Process Summary **Status**

Cold Space Data:

Product Loading Schedules:

Refrigerator Design Summary

Status

OAT data	set
System Type	Air-Air DX set
Refrigerant	R404a set
Evaporator	DXA set
Compressor	Recip set
Condenser	DAC set
Suction line H-X	set
Expansion valve	TEV set
Refrigerant lines	set
Defrost system	EHDF-Timed

Model Summary

Refrigerator Design-Point Data Calculation

Run Start and End Time:

Refrigerator Start-up Balance Point Data:

VCRmodel - Compressor Selection

Close Set Help

Compressor Selection

Semi-hermetic reciprocating

Semi-hermetic Screw

Recip design point compressor data

Polytropic efficiency = %

Mechanical efficiency = %

Clearance ratio = %

Maximum motor efficiency = %

Motor Maximum Power modulus =

% of motor heat absorbed by suction-gas = %

Compressor frame temperature = °C

Design Speed = rpm

% Speed = %

start | Sample Output 13 Fe... | A VCRmodel Softwar... | 2 Microsoft Office P... | 2 Visual Basic | EN | 07:32



Refrigerator design-point output screen

Design Balance Point Calculator

Close

Refrigerant = R404a COP = 2.6 Total refrigerant charge (kg) **28.57**

Compressor

Type: Recip. Suction Gas Cooled

Thermal capacity (kJ/K)	9.959
Swept volume (cc)	935.1
Pressure ratio =	4.54
Inlet temperature (oC)	23.6
Inlet pressure (kPa)	420.6
Discharge temperature (oC)	94.9
Discharge pressure (kPa)	1911.3
Refrigerant mass flow (kg/s)	0.424
Refrigerant vol. flow (m3/hr)	0.02
Mechanical power (kW)	21.91
Motor power input (kW)	23.07
Maximum motor power (kW)	25.377
Design speed (RPM)	1800
Volumetric efficiency (%)	78.4
Isentropic efficiency (%)	63.2
Mechanical efficiency (%)	97.9
Motor efficiency (%)	94.9
Overall efficiency (%)	58.8
Q-gain from motor cooling (kW)	1.038
Q-loss through casing (kW)	0.115
UA-value for case heat loss (W/K)	2.3

Expansion device

Type: TEV

π - constant 17.2036875307

β - constant 3.80786341224

Mass flow (kg/s) 0.424

Evaporator

Type: Air cooling DX type

Refrigerant-side

Q-rate (kW) =	60
Tsat (mean) (oC) =	-5
DT - superheat (K) =	5
Psat (mean) (kPa) =	517
P-loss (kPa) =	33.9
Charge (kg)	15.77
Thermal capacity (kJ/K)	63.47
P-loss coefficient ($\times 10^{-6}$)	0.11
Kfg heat transfer factor	224
Kg heat transfer factor	22
Liquid charge (kg)	15.597

Air-side

Tdb (on) (oC) =	5
%RH air-on =	70
Tdb (off) (oC) =	-2
Air-flow (kg/s) =	6.457
Air-flow (m3/s) =	5.098
P-loss (kPa) =	0.14
Motor power (kW) =	1.397
Condensate flow (g/s) =	0
Icing rate (g/s) =	5.779
P-loss coefficient	0.004
Face area (m2)	2.549

Condenser

Type: Air cooled type

Refrigerant-side

DP Q-rate (kW) = rate =	80
Tsat (mean) (oC) =	40
DT - subcooling (K) =	7
Psat(mean) (kPa) =	1822
P-loss (kPa) =	87.6
Charge (kg)	7.79
Thermal capacity (kJ/K)	1.36
P-loss coefficient ($\times 10^{-6}$)	0.25
Kfg heat transfer factor	395
Kf heat transfer factor	30.771
Liquid charge (kg)	6.43

Air-side

Tdb (on) (oC) =	30
Tdb (off) (oC) =	37
Air-flow (kg/s) =	11.3
Air-flow (m3/s) =	9.76
P-loss (kPa) =	0.15
P-loss coefficient	0.001
Fan efficiency (%)	57.6
Motor efficiency (%)	95
Fan shaft power (kW) =	2.54
Motor power (kW)	2.67
Max motor power (kW)	3.18
Face area (m2)	4.884
Ef	0.7

Pipe-line data

	DP (kPa)	Q (kW)	Tin (oC)	Tout (oC)	Pin (kPa)	Pout (kPa)	P-loss coef ($\times 10^{-6}$)	UA coef/MCp (kJ/K)
SL	79.8	0.661	0	1.7	500.4	420.6	0.01	0.039 1.84
HGL	44.1	-3.199	94.9	88.45	1911.3	1867.1	0.02	0.051 0.23
LL	43.4	-0.381	22.38	21.89	1779.5	1736.1	0.23	0.082 1.19

Suction-line heat exchanger

	Q-rate (kW)	Thermal capacity (kJ/K)	UA-value	Tin (oC)	Tout (oC)	Charge (kg)
	8.269	2.3	0.579	1.7	23.6	0.124
Vapour				33	22.3	2.89
Liquid						



The Simulator Run-Screen

Dynamic Cold-Store with DX Air-Air Refrigerator Model

End Run Model Break Plot Data Set Step Time

MODEL RUN-TIME

dayhourminTime step (sec)

Start time

Present time

End time

Store start-up temperature (oC)

Store start-up %RH

COLD STORE DATA

Store air temperature (oCdb)

Relative humidity of store air (%)

Humidity Ratio of store-air (g/kg)

Total store heat gain (kW)

Product heat rate (kW)

PRODUCT DATA

Loading schedule	Product	Surface temp (oC)	Mean temp (oC)	Units	
				In	Out
1	Pork Pies	0	80	1	0
2					
3					
4					
5					
6					
7					
8					
9					
10					

AMBIENT CONDITIONS

Outdoor ambient dry-bulb temperature (oC)

Outdoor ambient wet-bulb temperature (oC)

Outdoor ambient %RH

SYSTEM PERFORMANCE

Total Electrical Energy (kWh)

Electrical Power Input (kW)

Refrigerator COP

Refrigerator COSP

REFRIGERATOR STATE

REFRIGERATOR

DEFROST

Condenser fan speed (%)

Evaporator fan speed (%)

Thermostat Upper set-point

Thermostat Lower set-point

DOOR CLOSED

EVAPORATOR DATA

Heat rate (kW)

Off-Coil Air Temp (oCdb)

Off-coil Humidity Ratio (g/kg)

Air-flow (m3/s) =

Off-coil Air Velocity (m/s)

Mass of ice on coil (kg)

Tsat (mean) (oC) =

Refrigerator model

Transient data

Evaporator

DT - superheat (K) =

Refrigerant P-loss (kPa) =

Air inlet temp (oCdb)

Air inlet temp (oCwb)

Air P-loss (kPa) =

Fan power (kW) =

Condensate flow (g/s) =

Icing rate (g/s) =

Condenser

Q-rate (kW)

Tsat (mean) (oC) =

DT- subcooling (K) =

Refrigerant P-loss (kPa) =

Air inlet temp (oCdb)

Air outlet temp (oCdb)

Air-flow (m3/s) =

Air P-loss (kPa) =

Fan power (kW)

Compressor Data

Motor power input (kW)

Overall efficiency (%)

Speed (RPM)

Pressure ratio =

Inlet temperature (oC)

Discharge temperature (oC)

Refrigerant mass flow (kg/s)

Suction line heat exchanger

Q-rate (kW)

Refrigerant Lines

Suction line P-loss (kPa)

Liquid line P-loss (kPa)

Hot gas line P-loss (kPa)

Expansion device flow (kg/s)

start
Sample Outpu...
A VCRmodel S...
2 Microsoft ...
VCRmodel - Mi...
VCR v1.0: Sin...
Dynamic Cold-...
EN ⏪ ⏩ 07:40



Department for Environment Food and Rural Affairs

What the simulator provides

During RUN-TIME ...

- Information on the current Model-Time and operating mode of the refrigerator: ON/OFF, Defrosting ...
- Continuously updated product temperature information, total electrical power usage and CO₂ emissions, refrigerator performance data, store data: individual heating load gains and losses, temperature, relative humidity, ambient temperature,
- Interactive control of fan speeds and thermostat settings and Time-Step, so you can speed RUN-TIME up a bit.

Future developments

Additional component and system choices:

Fan-coils

Evaporative condensers

Pump-fed evaporators

Water-cooling evaporators

Cooling towers

Screw Compressors

Hot-Gas Defrost

Intelligent controls

Extend Properties Library

Multi-stage compression ...

Fault prediction and diagnosis



Concluding remarks ...

We believe that through the use of simulation software, of the type you have seen during this presentation, the energy efficiency of food refrigeration systems can be optimised to minimise the CO₂ emissions produced by industry.



Concluding remarks...

There was not time to show the two simulators during this short presentation, however if anyone wishes to see a demonstration over the lunch break please feel free to ask.

Thank you for listening

